Probing Lepton Flavor Violation at the ILC and CLIC

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Lepton flavor violation in the $\tau\mu$ sector would be a clear sign of Beyond Standard Model physics. We employ the SMEFT framework to study the process $e^+e^- \to \tau\mu$ at the ILC and CLIC. We find that the e^+e^- beam polarizations achievable at these machines allow us to probe the chirality structure of the SMEFT operators. In addition, the high center of mass energy leads to a substantial increase in sensitivity to the four-fermion operators that rivals, and in some cases, surpasses tau decay projections from Belle-II.

I.   INTRODUCTION

Lepton Flavor Violation (LFV) is a smoking gun signature for Beyond Standard Model (BSM) physics as it is highly suppressed in the Standard Model (SM) [1–4]. We focus on heavy new physics with a UV scale above the center of mass energies of the colliders $\Lambda \gtrsim \sqrt{s}$, which we parametrize by the Standard Model Effective Field Theory (SMEFT) [5]. We compute the cross section of the LFV process $e^+e^- \to \tau\mu$ for arbitrary e^+e^- beam polarizations, and include the impact of Initial State Radiation (ISR) on the signal. We compare the sensitivity projections of the ILC and CLIC to those obtained from the Belle-II experiment that is searching for the related process $\tau \to \mu e^+e^-$.

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II.   OBSERVABLES

Three classes of operators contribute to $e^+e^- \to \tau\mu$ at tree-level: dipole operators, Higgs current operators and four-fermion operators. The total cross section is given by

$$
\sigma(e^+e^- \to \tau\mu) = \frac{m_Z^2}{64\pi\Lambda^4}\Bigg[(1+P_+)(1+P_-)\Big(I^{e_R^+e_R^-}(s)+\bar{I}^{e_R^+e_R^-}(s)\Big)+(1-P_+)(1-P_-)\Big(I^{e_L^+e_L^-}(s)+\bar{I}^{e_L^+e_L^-}(s)\Big)
$$
$$
+\frac{2}{3}(1+P_+)(1-P_-)\Big(2I_0^{e_R^+e_L^-}(s)+2\bar{I}_0^{e_R^+e_L^-}(s)+I_2^{e_R^+e_L^-}(s)+\bar{I}_2^{e_R^+e_L^-}(s)\Big)
$$
$$
+\frac{2}{3}(1-P_+)(1+P_-)\Big(2I_0^{e_L^+e_R^-}(s)+2\bar{I}_0^{e_L^+e_R^-}(s)+I_2^{e_L^+e_R^-}(s)+\bar{I}_2^{e_L^+e_R^-}(s)\Big)\Bigg] . \quad (1)
$$

where the $I^{e^+e^-}$ coefficients depend on the SMEFT coefficients and the e^+e^- helicities. P_- characterizes the polarization of the electron beam and P_+ characterizes the polarization of the positron beam. For detailed calculations as well as expressions for the coefficients, see Refs. [6, 7]. An important qualitative feature is the linear growth of the cross section with s in the presence of four-fermion operators.

III.   EXPECTED SENSITIVITIES AT ILC AND CLIC

Signal Simulation The cross section is convoluted simultaneously with the ISR radiator functions for both the e^+e^- beams [8], and with Gaussian distributions to account for the beam energy spread and the detector momentum resolution. We use a Monte Carlo (MC) procedure that unfolds in four stages. First, we sample two beam momenta from Gaussian distributions with a mean of $\sqrt{s}/2$ and with a standard deviation corresponding to the beam energy spread. Second, we sample from the ISR radiator functions for the electron/positron to lose a longitudinal momentum fraction. Third, we sample the momentum of the emitted muon from the differential cross-section as a function of momentum p in the lab frame

$$
\frac{d\sigma}{dp} = \frac{4}{\sqrt{s}}\frac{1}{(x_- - x_+)}\frac{d\sigma}{d\cos\theta} \quad \text{for } \min(x_-,x_+)\frac{\sqrt{s}}{2} < p < \max(x_-,x_+)\frac{\sqrt{s}}{2} . \quad (2)
$$

Here, the momentum of the e^- (or e^+) is $x_-\sqrt{s}/2$ (or $x_+\sqrt{s}/2$) and θ is the angle between the electron and the outgoing muon in the center of mass frame. Finally, we smear the muon momentum with the detector momentum resolution according to a Gaussian distribution.
Backgrounds To diminish background from $e^+e^- \to \mu^+\mu^-$ where a muon is misidentified as a

tau, we select only the hadronic tau decay channels $\tau_{\text{had}} \to \rho\nu \to 2\pi\nu$, and $\tau_{\text{had}} \to 3\pi\nu$. The remaining backgrounds due to $e^+e^- \to W^+W^- \to \tau_{\text{had}}\nu\mu\nu$, $e^+e^- \to W^+W^- \to \tau_{\text{had}}\nu\tau\nu \to \tau_{\text{had}}\mu 4\nu$ and $e^+e^- \to ZZ \to \tau_{\text{had}}\tau\nu\nu \to \tau_{\text{had}}\mu 4\nu$ are suppressed by imposing a cut ($x \gtrsim 1$) on $x = p_\mu/p_{\text{beam}}$, where p_μ is the absolute value of the muon momentum in the lab frame and p_{beam} is the beam momentum [9].

Beam energy spread and finite momentum resolution of the detector shifts the endpoint of the muon momentum from the process $e^+e^- \to \tau_{\text{had}}\tau \to \tau_{\text{had}}\mu\bar{\nu}\nu$ to be slightly above $x = 1$ leading to a diminished background (as opposed to an $O(1)$ portion of the signal) to survive after the cut. The number of expected signal and background events are given by

$$N_{\text{sig}} = \mathcal{L}_{\text{int}} \times \sigma(e^+e^- \to \tau\mu) \times \mathcal{B}(\tau \to \text{had})\epsilon_{\text{had}} \times \epsilon_{\text{sig}}^x \times \epsilon_{\text{sig}}^{\text{ang}} \, , \tag{3}$$

$$N_{\text{bkg}} = \mathcal{L}_{\text{int}} \times \sigma(e^+e^- \to \tau^+\tau^-) \times 2 \times \mathcal{B}(\tau \to \text{had})\epsilon_{\text{had}} \times \mathcal{B}(\tau \to \mu\nu\nu) \times \epsilon_{\text{bkg}}^x \times \epsilon_{\text{bkg}}^{\text{ang}} \, , \tag{4}$$

where $\mathcal{L}_{\text{int}}$ is the integrated luminosity, $\epsilon_{\text{sig/bkg}}^x$ are the cut efficiencies, $\epsilon_{\text{sig/bkg}}^{\text{ang}} \simeq 98\%$ are the angular efficiencies and $\mathcal{B}(\tau \to \text{had})\epsilon_{\text{had}}$ is the branching ratio to two or three pions multiplied by their respective identification efficiencies. The center-of-mass energies, polarizations, luminosities, beam energy spreads and detector momentum resolutions can be found in Refs. [10, 11] for the ILC and in Refs. [12–14] for CLIC.

<u>Results</u> The criterion $N_{\text{sig}} \geq 2\sqrt{N_{\text{bkg}} + N_{\text{sig}}}$ provides us with an estimate of the sensitivity at 2σ. The main results are shown in Figures (1) and (2) with a description in the Figure captions.

IV. CONCLUSION

We gain exceptional sensitivity to four-fermion operators due to their linear scaling with s and the high center of mass energy of linear colliders, especially CLIC. The different polarizations of the e^+e^- offers an additional handle that allows us to probe the chirality structure of the operators.
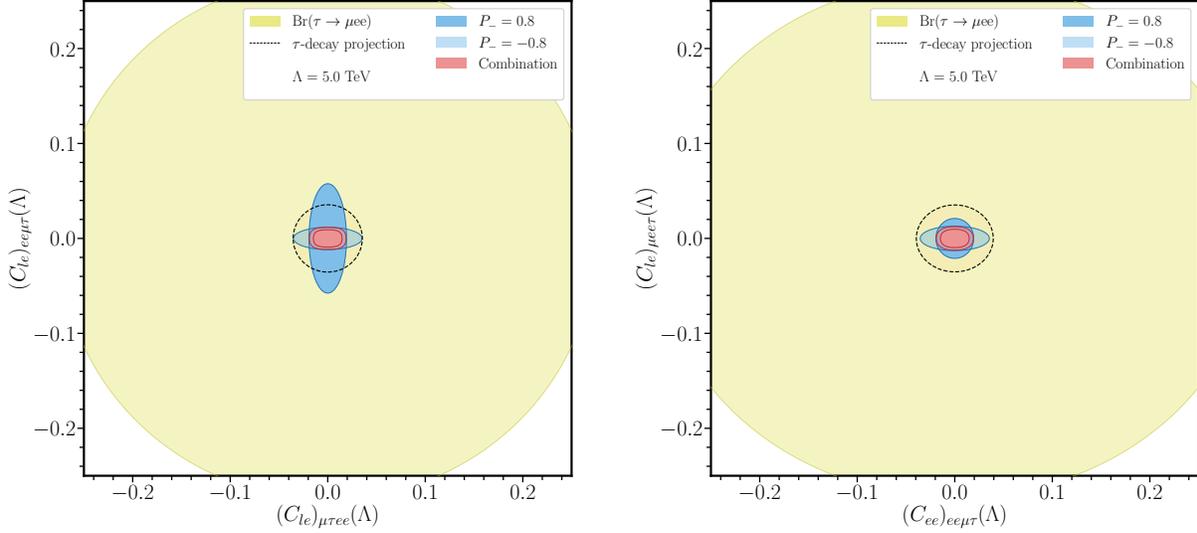
V. ACKNOWLEDGEMENTS

FIG. 1. Adapted from [6]. Sensitivity to pairs of SMEFT coefficients at the $\sqrt{s} = 3\,\text{TeV}$ run at CLIC. The various shades of blue represent our 2σ sensitivity projections for different e^+/e^- beam polarizations in the process $e^+e^- \to \tau\mu$. The lighter and darker red regions correspond to the combined 2σ and 1σ constraints, respectively. The yellow region indicates the current 2σ bounds from searches for the $\tau \to \mu e^+e^-$ decay at BaBar and Belle [15, 16], while the solid dashed line shows the expected sensitivity projection from Belle II [17]. The UV scale is fixed to $\Lambda = 5$ TeV.
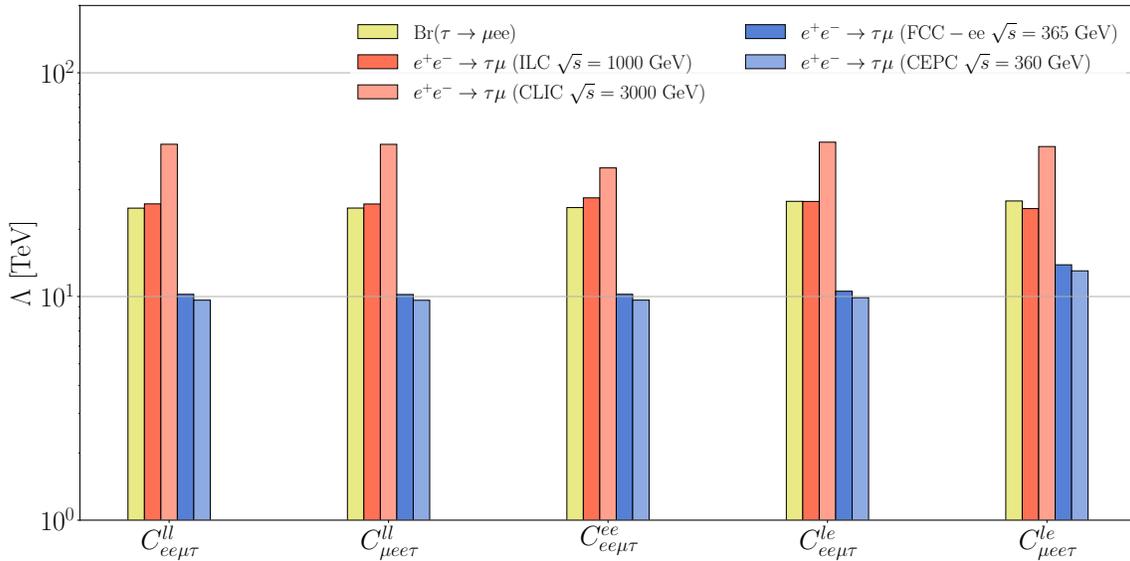

FIG. 2. Adapted from [6]. Sensitivity to the new physics scale Λ from $\tau \to \mu e^+e^-$, and from the process $e^+e^- \to \tau\mu$ at future colliders. Each SMEFT Wilson coefficient is set to a value of unity at the scale Λ ($C_i(\Lambda) = 1$), with all others set to zero. Only projected sensitivities are shown.

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